Thermo-mechanical Fatigue Behaviour of AlSi7Mg Alloy Processed by Selective Laser Melting

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Abstract

Heat treatable hypo-eutectic AlSi7Mg (A357) alloy is widely used for lightweight structural parts and for high temperature applications such as in cast cylinder heads.
AlSi7Mg is also a suitable alloy to be processed by selective laser melting (SLM), owing to its narrow solidification range, resistance to hot cracking and good fluidity. Employing SLM-processed parts made by AlSi7Mg in high temperature applications with cyclic thermal loads requires good resistance to thermo-mechanical fatigue due to the critical strains and stresses induced by the fluctuating temperature. In this study, the thermo-mechanical fatigue behaviour of A357 alloy samples produced by SLM has been investigated using a Gleeble®3800 simulator. A correlation has been found between the applied mechanical stress and thermo-mechanical fatigue life. Analyses on the mechanisms of failure allowed to draw conclusions about the relation between the thermo-mechanical fatigue strength and peculiar microstructure formed by SLM-processing.

Keywords

Selective laser melting, AlSi7Mg, Thermo-mechanical fatigue, Damage mechanisms

Introduction

Selective laser melting (SLM) is an additive manufacturing (AM) technique which allows the production of parts layer by layer, based on a digital 3-D model that drives the melting of selected areas on a powder bed by a high-power laser beam [1–3]. In recent years, this method attracted a lot of attention for different industrial applications because of the possibility to produce complex parts, to reduce the production time of prototypes and for small production batches, to decrease the part's weight and raw material wastes, and to implement new functions in single components [4]. Automotive, aerospace and biomedical appear as the most important industrial fields for modern AM technologies [5].

Among the alloys that have being used currently as feedstock materials for SLM, Al alloys are among the most important candidates. Particularly, hypo-eutectic AlSi7Mg (A357) alloy is of great interest, because it presents a good compromise between strength and ductility in conjunction with high corrosion and wear resistance, which make it suitable for casting parts in automotive and aerospace fields [6, 7]. The properties of A357 alloy that make it appropriate to be produced by casting as by SLM are resistance to hot cracking, good fluidity and narrow solidification range [8, 9].

Thermo-mechanical fatigue (TMF) due to the combined effect of fluctuating mechanical and thermal loads, can occur in different industrial applications such as in cylinder heads and exhaust manifolds [10]. Several studies investigated the influence of different parameters on TMF behaviour of cast Al alloys. P. Huter et al. [6] demonstrated that optimisation of the combination of matrix ductility, thermal stability and crack propagation characteristics resulted in improvement of TMF life of hypo-eutectic cast Al alloys. H. Toda et al [11] showed that higher solidification rate led to better TMF life of cast Al-Si alloys. Javidani et al. [12] noted that TMF life of the Al-Si alloys are affected more by casting process (hence by the achieved microstructure and by the presence of solidification defects) than by the alloy chemistry. Indeed, lower level of porosity and inclusions resulted in superior TMF behaviour.

SLM parts have some peculiar differences in microstructural features and defects with respect to as cast parts that result in a different behaviour under TMF. Defects in SLM parts are categorized in several types such as spatters, partially melted powder particles and balling as surface features, and in porosity, lack of fusion and cracks as volume defects. Spatters that are produced due to the intense interaction of the laser beam with the melt pool and vapours in the chamber, can in turn induce cavities and pores formation due to the lack of powder feeding around them [13, 14]. These defects can especially have a detrimental effect on TMF life of components that requires to be more deeply investigated.
In this paper, TMF behaviour of SLM-processed AlSi7Mg alloy, aged at 160°C to peak hardness [15], has been investigated by tests at constant applied loads with cyclic temperature fluctuations by a Gleeble®3800 equipment. Microstructural analyses together with hardness characterization and analyses of fracture surfaces have been performed on the tested specimen in order to obtain a comprehensive overview of TMF life of SLM materials.

Materials and experimental methods

TMF test specimens were processed by SLM using a Renishaw AM250 system. The Renishaw AM250 system employs a single mode fibre laser with maximum power of 200 W and a focused spot size of 75 µm. Table 1 shows the process parameters that were employed for printing the samples. A meander scanning strategy was used for producing the specimens, with a rotation of the scanning direction of 67° with respect to previous layer.

Process parameter	Value
Laser power	200 W
Exposure time	140 µs
Point distance	80 µm
Hatch distance	115 µm
Layer thickness	25 µm
Focal point	1 mm (above the powder bed)
Atmosphere	Argon

Table 1 Process parameters used for the printing of the TMF specimens.

Samples were printed by using commercial gas atomized AlSi7Mg alloy (A357) powder (supplied by LPW South Europe Srl) with a particle size distribution in the range of 20÷63 µm. The chemical composition of the powder is reported in Table 2.

Si	Mg	Fe	Cu	Mn	N	O	Ti	Zn	Al
6.5	0.58	0.1	<0.05	<0.1	<0.2	0.1	0.12	<0.1	Bal.

Table 2 Chemical composition (wt. %) of the investigated AlSi7Mg powder (data provided by the powder supplier).

The SLM processed samples were artificially aged at 160°C from the as built condition for 4 hours to reach peak hardness condition. Then, cylindrical dog-bone samples were machined to achieve a gauge length of 15 mm and a diameter of 8 mm for TMF tests as shown by the drawing in Figure 1. The density of the samples was in the range of 99.6÷99.8%.

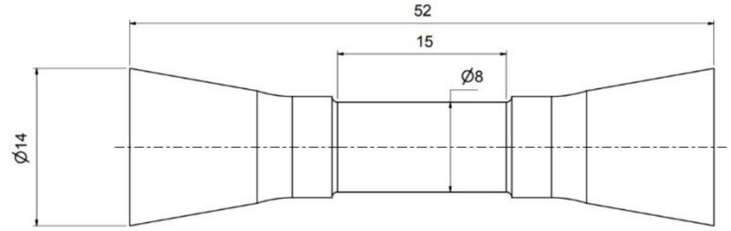


Figure 1 Sketch of TMF test specimen (in mm).

The TMF experiments were carried out using a thermo-mechanical simulator type Gleeble®3800 in stress-controlled mode. Temperature cycling was done by direct resistance heating and air cooling with heating and cooling rates set at 30K/s. The temperature and the strain of each specimen were measured by a thermocouple welded at the sample's surface and an extensometer, respectively. The temperature range was set between 100 and 280°C. TMF experiments in the low cycle fatigue regime were performed under constant stress value, ranging from 90 to 120 MPa. The tests replicated for the stress values of 110, 115 and 120 MPa for results confirmation. One thousand cycles were set as the run-out value. At the beginning of each experiment, the load was applied to the specimen at room temperature and then thermal cycling was started.
Fracture surfaces of the tested samples were then observed by means of Scanning Electron Microscopy (SEM). Selected specimens were also sectioned longitudinally along their axes and observed after metallographic preparation by SEM and Light Optical Microscopy (LOM). Hardness drop caused by TMF experiments was measured by EMCO-TEST M1C010 hardness machine by performing Vickers indentations with a load of 300 g.

Results and discussion

The TMF experiments were done on a total of 10 samples. Samples tested at the stress level of 90, 95, 100 and 105 MPa didn't break till run out. At the stress level of 110 MPa, one sample failed after 913 cycles while the other one didn't fail till run out. Under the stress of 115 MPa both samples failed by number of cycles of 442 and 872. Eventually, samples were broken after 266 and 326 cycles at the stress of 120 MPa. It can be therefore reasonably considered that 105 MPa is the threshold value of stress for TMF life under the investigated experimental conditions. Figure 2 summarizes the TMF behaviour of the tested alloy.

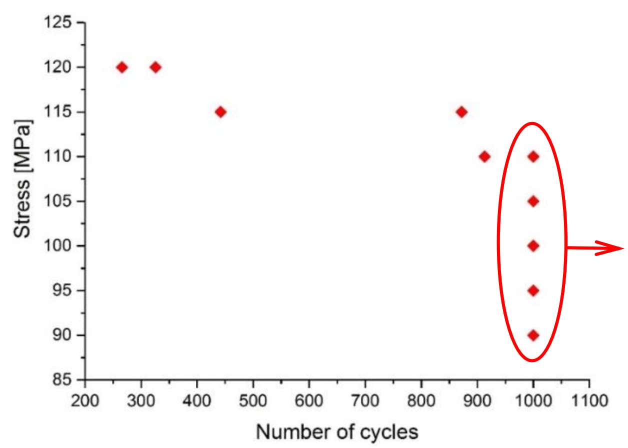
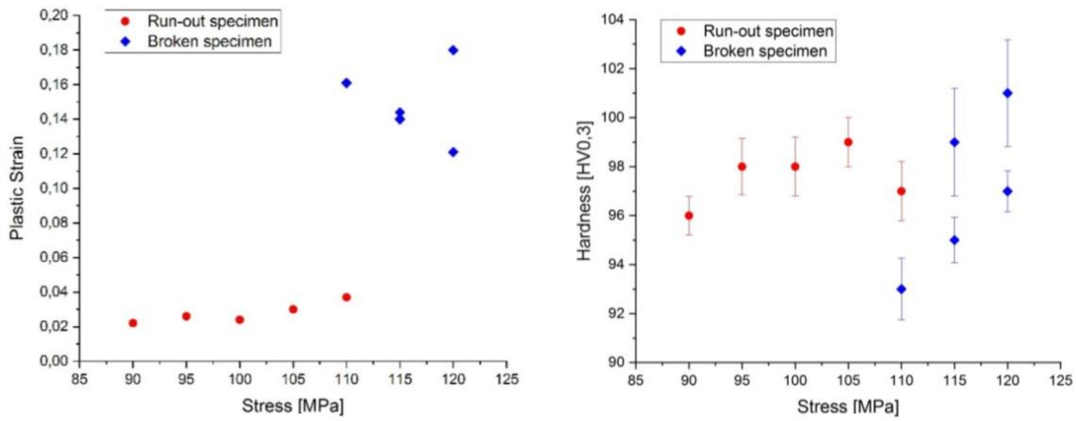


Figure 2 TMF lifetime of the samples with respect to the stress.

Figure 3a illustrates the trend of the plastic strain caused by TMF experiments for different specimens evaluated theoretically by subtracting the elastic and thermal strains from the total strain. Broken samples show plastic strain values, about five times higher than run-out specimens. Hardness Vickers of the TMF tested samples together with standard error of measures for each sample are shown in Figure 3b. As it can be seen, TMF experiments lead to hardness drop from 123 HV to 93÷101 HV. The value of the hardness drop is not affected considerably by the value of applied mechanical load. Even though, it is clear that the high temperature of 280°C created coarser precipitates.
Figure 4 shows representative fracture surfaces of two TMF tested specimens. As it can be seen, the fracture occurred in ductile mode with presence of dimples. It was mentioned in the introduction that the pores and cavities can already be present in the original SLM printed samples mainly due to the effects by spatters during SLM processing. These pores and cavities can be recognized on the fracture surfaces in Figures 4a and 4c having them the largest size (shown by red arrow in Figure 4d). In addition to the pre-existing defects, ductile micro-dimples (indicated by yellow arrow in Figure 4b) formed due to the plastic deformation during TMF experiments and these add to the population of the visible pores found on the fracture surface. As it is observable, ductile tearing can be seen in the internal parts of the largest cavities and dimples, in agreement to the typical features of ductile fracture.



(a) **(b)**

Figure 3 (a) Plastic strain due to TMF test vs. stress, (b) Hardness values with standard error after TMF tests vs. stress.

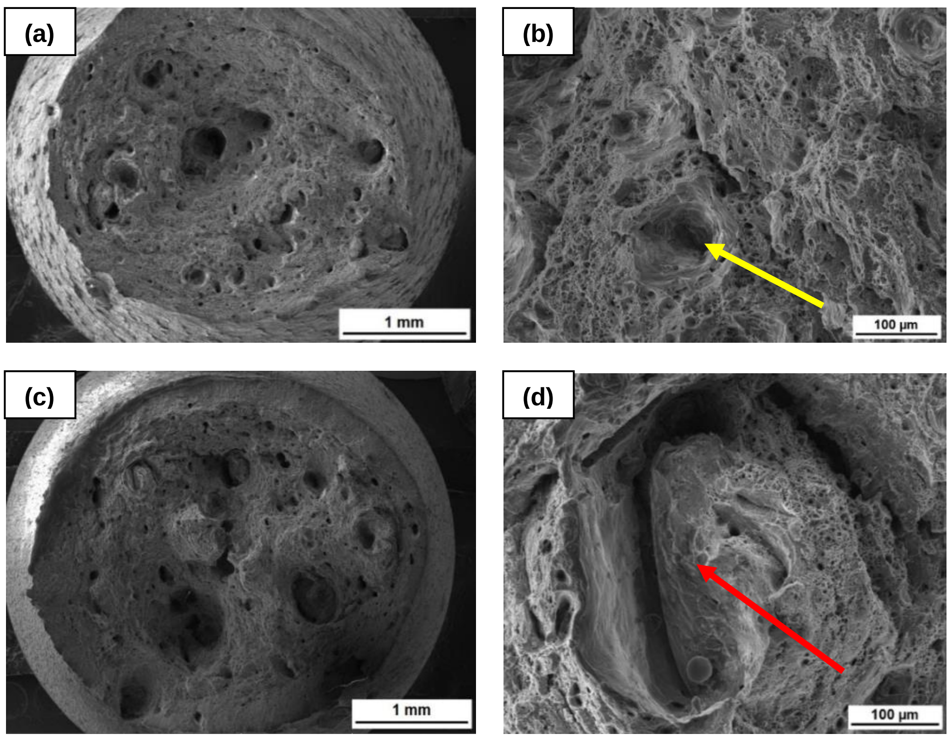


Figure 4 Fracture surface morphology of TMF test specimens under the stress of: (a) and (b) 120MPa, (c) and (d) 115MPa (Figures 4b and 4d illustrate magnified SEM images of Figures 4a and 4c, respectively).

Figure 5 shows cross-section views of the samples obtained by SEM and LOM. Back Scattered Electron (BSE) microscopy of the samples (Figures 5a and 5b) shows porosities and voids with irregular shape. These pores are commonly created close to spatters, which are a typical of SLM parts, as discussed in previous paragraph.

Crack initiation could often be observed around these pores, especially at their sharp corners. These pores are often filled with unmelted powder particles. Pores with sharp corners have a detrimental effect on TMF life of the samples, since the notch effect in these areas lead to higher stress with respect to the nominal applied load [3]. LOM images of the sectioned samples (Figures 5c and 5d) depict crack nucleation and propagation from the pores, too. Figures 5e and 5f indicate debonding among spatter and the matrix of the alloy (shown by red arrows) which also causes the shortening of the TMF life of the samples.

The full investigation is still in progress in order to find a better correlation between the microstructural features and the results of the TMF life of the SLM-processed AlSi7Mg alloy.

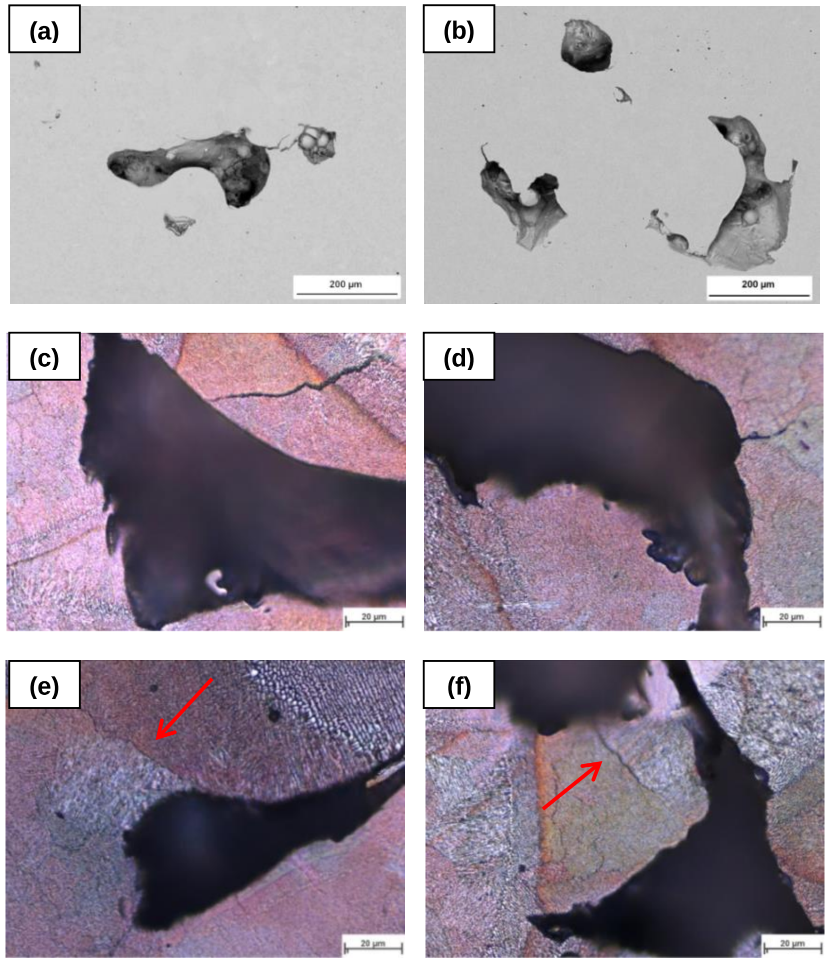


Figure 5 Pores and crack origination presented by: (a-b): SEM (BSE-mode) images; (c-d): LOM images of TMF tested samples.

Conclusions and future plan

In the presented study the thermo-mechanical fatigue behaviour of SLM-processed AlSi7Mg specimens tested by a Gleeble simulator was investigated. The main results achieved from microstructural and mechanical analysis are the following:

- There is a correlation between the value of the applied stress and the number of the cycles to failure of the specimens, while keeping thermal conditions constant. Under the stress of 110 MPa one sample out of two failed at 913 cycles, while at the stress of 115 and 120 MPa, all the samples broke after the average cycles of 657 and 296, respectively. The results show that the stress value of 105 MPa can be considered as threshold value for TMF life of the components under the investigated experimental conditions.
- The hardness of all samples decreased after the TMF tests. Hardness drop value is not affected greatly by the value of the applied load.
- A high degree of plastic strain can be observed in the fractured specimen. Indeed, fractographic analyses revealed a ductile fracture mode with presence of both coarse dimples nucleated from SLM-process induced pores and micro-dimples formed due to plastic deformation during TMF tests.
- Microstructural analysis revealed the presence of cracks originated at the edges of the pores. These cracks propagated during the experiment and resulted in final rupture of the samples under the stress values of 110, 115 and 120 MPa.

To the author's knowledge, the data for TMF behaviour of cast A357 alloy under similar experimental condition are not provided in the literature. Future research will explore the comparison between the current results and the behaviour of cast A357 alloys tested under similar conditions.

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Bibliography

[1] Thompson, M. K.; Moroni, G.; Vaneker, T.; Fadel, G.; Campbell, R. I.; Gibson, I.; Bernard, A.; Schulz, J.; Graf, P.; Ahuja, B.; Martina, F. (2016). Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints, CIRP Annals, Vol. 65, No. 2, 737–760. doi:10.1016/J.CIRP.2016.05.004
[2] Osakada, K.; Shiomi, M. (2006). Flexible manufacturing of metallic products by selective laser melting of powder, International Journal of Machine Tools and Manufacture, Vol. 46, No. 11, 1188–1193. doi:10.1016/J.IJMACHTOOLS.2006.01.024
[3] Smelov, V. G.; Sotov, A. V; Agapovichev, A. V; Tomilina, T. M. (2016). Selective Laser Melting of Metal Powder Of Steel 3161, IOP Conference Series: Materials Science and Engineering, Vol. 142, 12071. doi:10.1088/1757-899x/142/1/012071
[4] J. Sames, W.; A. List, F.; Pannala, S.; Dehoff, R.; Babu, S. (2016). The Metallurgy and Processing Science of Metal Additive Manufacturing, International Materials Reviews (Vol. 61). doi:10.1080/09506608.2015.1116649
[5] DebRoy, T.; Wei, H. L.; Zuback, J. S.; Mukherjee, T.; Elmer, J. W.; Milewski, J. O.; Beese, A. M.; Wilson-Heid, A.; De, A.; Zhang, W. (2018). Additive manufacturing of metallic components – Process, structure and properties, Progress in Materials Science, Vol. 92, 112–224. doi:10.1016/J.PMATSCI.2017.10.001
[6] Huter, P.; Oberfrank, S.; Grün, F.; Stauder, B. (2016). Thermo-Mechanical Fatigue Influence of Copper and Silicon on Hypo-Eutectic Al–Si–Cu and Al–Si–Mg Cast Alloys Used in Cylinder Heads, International Journal of Fatigue (Vol. 88). doi:10.1016/j.ijfatigue.2016.02.017
[7] Rao, H.; Giet, S.; Yang, K.; Wu, X.; Davies, C. H. J. (2016). The influence of processing parameters on aluminium alloy A357 manufactured by Selective Laser Melting, Materials & Design, Vol. 109, 334–346. doi:10.1016/J.MATDES.2016.07.009
[8] Kores, S.; Zak, H.; Tonn, B. (2008). Aluminium Alloys for Cylinder Heads, RMZ - Mater Geoenviron (Vol. 55)
[9] Aversa, A.; Lorusso, M.; Trevisan, F.; Ambrosio, P. E.; Calignano, F.; Manfredi, D.; Biamino, S.; Fino, P.; Lombardi, M.; Pavese, M. (2017). Effect of Process and Post-Process Conditions on the Mechanical Properties of an A357 Alloy Produced via Laser Powder Bed Fusion, Metals . doi:10.3390/met7020068
[10] Bartsch, K.; Hänninen, H.; Nieminen, M. (1993). Thermal Fatigue: A Literature Review, NASA STI/Recon Technical Report N
[11] Toda, H.; Katano, J.; Kobayashi, T.; Akahori, T.; Niinomi, M. (2005). Assessment of Thermo-Mechanical Fatigue Behaviors of Cast Al-Si Alloys by Experiments and Multi-Step Numerical Simulation, MATERIALS TRANSACTIONS, Vol. 46, No. 1, 111–117. doi:10.2320/matertrans.46.111
[12] Javidani, M.; Larouche, D. (2014). Application of cast Al–Si alloys in internal combustion engine components, International Materials Reviews, Vol. 59, No. 3, 132–158. doi:10.1179/1743280413Y.0000000027
[13] Nasab, M. H.; Gastaldi, D.; Lecis, N. F.; Vedani, M. (2018). On morphological surface features of the parts printed by selective laser melting (SLM), Additive Manufacturing, Vol. 24, 373–377. doi:10.1016/J.ADDMA.2018.10.011
[14] Gasper, A. N. D.; Szost, B.; Wang, X.; Johns, D.; Sharma, S.; Clare, A. T.; Ashcroft, I. A. (2018). Spatter and oxide formation in laser powder bed fusion of Inconel 718, Additive Manufacturing, Vol. 24, 446–456. doi:10.1016/J.ADDMA.2018.09.032
[15] Casati, R.; Vedani, M. (2018). Aging Response of an A357 Al Alloy Processed by Selective Laser Melting, Advanced Engineering Materials. doi:10.1002/adem.201800406